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Assessing future water resource constraints on thermally based renewable energy resources in California

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HIGHLIGHTS

- Water availability can limit solar thermal and geothermal resource utilization.
- Regional water availability is more important than cooling type for resource utilization.
- Spatially targeted water demand reductions enable increased resource utilization.
- Sustainable water-based limits should factor into in resource expansion planning.

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ABSTRACT

In this study, we investigate the extent to which physical water resource availability constraints can limit the deployment of solar thermal and geothermal-based energy resources under future climate scenarios in California. This is accomplished by (1) calculating the water unconstrained potential capacity for solar thermal and geothermal power plants, (2) estimating the available water supply for supporting the water needs of these plants using four climate model simulations under representative concentration pathway (RCP) 8.5, and (3) determining the supportable capacity from the available water supply based on power plant cooling type. We show that regional water availability can limit the installable capacity of solar thermal resources to a range of 10.9–52.6% of solar thermal potential and geothermal resources to between 17.9% and 100% of geothermal potential, depending on cooling system and regional water demand levels by the year 2050. The limiting factor for installable capacity was driven by whether the locations of solar thermal and geothermal resources were spatially aligned with precipitation patterns, with cooling system type acting as a secondary factor. In regions with high solar thermal and geothermal potential, reducing water demand from other sectors was important for alleviating the water constraints on solar thermal and geothermal capacity and increasing total resource potential. Water conservation policies can therefore support the deployment of renewable energy resources and should be considered in future water and energy resource planning.

1. Introduction

Impacts of conventional fossil fuel energy use on the climate, environment and human health have motivated the accelerated deployment of low-carbon and renewable energy resources. In California, many studies have designed optimal pathways to reach the renewable portfolio standard goals, determining the best mixture of low-carbon and renewable energy resources based on different criteria.

Studies have examined the use of economy-wide technology transformations to meet the desired emissions target by 2050 and used energy modeling to determine cost-effective energy technology investments under a range of policy and technical constraints [1,2]. In these studies, solar thermal and geothermal resources were identified as fulfilling varying roles in contributing to the renewable resource mix based on characteristics such as dispatchability and the use of conventional technologies.

Solar thermal and geothermal power plants are based on Rankine-cycle steam turbine power plant configurations, which carry out heat rejection in the condenser by externally cooling the working fluid. This is accomplished by using recirculating or evaporative water cooling systems, which require significant water inputs to provide the required level of cooling. Alternatively, dry cooling systems utilize air, but at a

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higher cost and lower cooling efficiency. Even with dry cooling, water consumption is not eliminated in steam-turbine based power plants, since facilities use make-up water for the main working fluid loop, on-site facility operations, and for cleaning the solar thermal collectors.

In recent years, the characterization of water use in the energy sector and its implications for energy resources has been a topic of considerable research interest. The U.S. Department of Energy [3] conducted a study in 2014 to identify and quantify interactions between energy and water, especially with regards to power plant cooling, finding that thermoelectric power generation utilized 68 billion gallons per day of water and represented the sector with the largest water withdrawal amounts. The Public Policy Institute of California (PPIC) characterized the interconnections between energy and water use in California in 2016 [4], finding that water end-uses (i.e. water heating, process water pressurization, etc…) comprise 88% of the water-related energy use in the state. The use of energy for water in California was also characterized by Cohen et al. [5], who focused on the costs associated with energy for water pumping in conveyance systems and from groundwater aquifers.

The impacts of drought and climate change on hydropower generation have been examined by Gleick [6] under current conditions concluding that climate change induced drought caused increases in natural gas usage through from 2011 to 2015 and Tarroja [7] under projected future conditions, concluding that hydropower variability reduced the efficiency of electric grid operations. Sanders [8] and Peer [9] have characterized the impact of these interactions on electric grid and water resources by investigated the impact of water prices on power plant water use efficiency [10]. These studies found that water fees can reduce water withdrawals by up to 75% but with the tradeoff of increasing wholesale electricity prices by up to 120%. Similar analyses were performed by DeNooyer for Illinois [11], finding that water fees can incentivize cooling system refits on thermal power plants. Stillwell [12,13] investigated alternative water supplies for thermoelectric power plant cooling and examined the feasibility of low water-use cooling technologies, finding that both strategies resulted in significant water savings for local river basins. Lubega [14] focused on this topic in the context of grid reliability, finding that low water-use cooling systems can improve electric system reliability during heat waves. Cooley [15] has also examined future water needs to support electricity production in the Western United States, with detail into the connections between different energy-sector processes and impacts on systems that provide water resources and maintain water quality. Escriva-Bou [16,17] has also investigated patterns for residential water use and related energy and greenhouse gas emissions in California. Arent [18] examined the implications of high renewable deployment for water use among other environmental metrics such as land and material use, concluding that renewable deployment reduced water use by 50%. Li [19] examined regional water conservation in China from the power generation sector in 2030, highlighting spatial misalignment between water resource availability and water demand. In the broader water-energy nexus scope, studies regarding the optimization of policy have been conducted by Gjorgiev [20]. Many tools for informing the planning of water and energy infrastructure development within this context have also been developed [21,22].

As of 2016, solar thermal and geothermal capacity in California is 1.2 GW and 2.8 GW, respectively [23,24]. As early as 1983, solar thermal facilities were being built in California's Mojave Desert with the Solar Electric Generating Station series of power plants. Solar thermal capacity remained stagnant until 2014, when these power plant types experienced renewed interest due to the Renewable Portfolio Standards. Solar thermal resources represent an important component of a utility's renewable portfolio, as thermal storage can be a cheaper alternative to electrical energy storage. Geothermal capacity in California has also remained relatively constant since 2001, but has recently been experiencing renewed interest due to the dispatchability of this resource in comparison to wind and solar.

While interactions between the water and energy sectors have been examined from a variety of standpoints, previous studies have not quantified how water availability can constrain the deployment of renewable energy resources. The majority of the literature has focused on characterizing the water usage of the energy sector or vice versa, but has not applied water use constraints to inform energy resource planning. In California, most of the solar thermal and geothermal potential is located in the southeastern desert areas. However, these regions tend to be water-limited due to local climate conditions, which can constrain the installable capacity of power plants. This limitation may be exacerbated under climate change depending on future shifts in regional water availability [25,26]. Therefore, this study examines how projected changes in water availability will affect the installable capacity of solar thermal and geothermal resources in California and quantifies the contribution of thermally-based renewables in meeting the state's emissions reduction and renewable utilization goals. Our analysis focuses on constraints due to water availability based on atmospheric forcing. This analysis is not intended to examine perturbations from water rights and policy changes, although the study results have implications for future changes in both domains.

2. Methodology

In each of California's hydrologic regions, we calculated the potential installable capacity of solar thermal and geothermal resources based on energy potential. Using climate model projections, we also calculated the available supply of water by conducting a water balance of each hydrologic region. With the available water supply data, we determined the water-constrained installable capacity for each resource considering the water consumption intensity for solar thermal and geothermal power plants in different cooling system configurations. A general overview of the methodology is presented visually in Fig. 1.

2.1. Calculating water-unconstrained solar thermal and geothermal capacity

For solar thermal, we defined installable capacity as the potential usable capacity of solar thermal resources given practical constraints such as land use. We determined land exclusions by removing areas on which solar thermal power plants cannot be installed. We overlaid the remaining land area with solar insolation potential and parameters for the efficiency and capacity factors of a representative solar thermal power plant to determine the installed capacity. For geothermal, installable capacity refers to the potential usable capacity of these resources given the physical suitability of geographic sites to support hydrothermal systems. For geothermal, we utilized available estimates for hydrothermal capacity availability in California.

2.1.1. Solar thermal land exclusions

This analysis excluded lands under the following categories:

- **U.S. Federal Protected Lands**, which encompass all land areas protected from development by United States federal law. The U.S. Geological Survey (USGS) provides data on federally protected lands, including national parks and landmarks.
- **Unsuitable Land Cover**, which refer to land areas on which solar thermal power plants cannot be built due to the physical unsuitability for construction or the current use of the area. We obtained land cover data from the Multi-Resolution Land Characteristics Consortium for different categories using the 2011 National Land Cover Database (NLCD 2011) [27]. Of the land cover types in the 2011 NLCD, the following are assumed to be unsuitable land areas for constructing solar thermal power plants. Descriptions are from the NLCD documentation. The dataset is presented visually in the Supplemental Information.
  - o <u>Wetlands</u>: Woody Wetlands and Emergent Herbaceous Wetlands

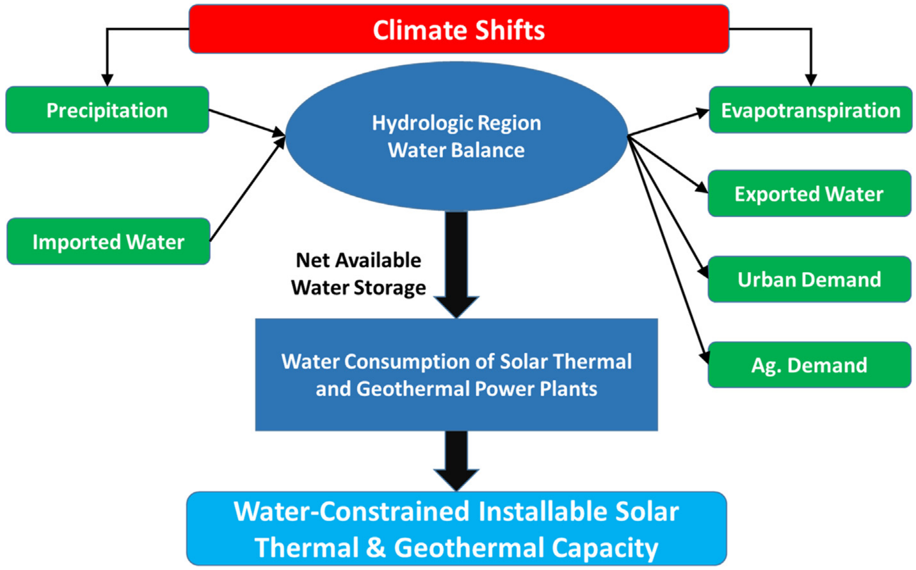

Fig. 1. Overview of methodology.

- o Open Water
- o Developed Land: Open, Low Intensity, Medium Intensity, and High Intensity. This includes urban areas
- o Forests: Deciduous Forest, Evergreen Forest, and Mixed Forest
- o Agricultural Lands: Pasture/Hay and Cultivated Crops
  - ■ While the conversion of agricultural land for energy production purposes has occurred in the past, over time, this practice has the potential to significantly impact the food sector [28–30]. We used the conservative assumption that agricultural lands are unavailable for solar thermal deployment since we did not model food sector interactions.
- **Land with Slope > 3% Grade**, which refers to land surfaces that exhibit slopes higher than a 3% grade. We used the assumption that relatively flat ground is needed to maintain alignment for large solar collectors, especially with trough systems. This assumption was also used by the National Renewable Energy Laboratory (NREL) assessment of technical renewable potential [31]. The land area was determined using land cover data from the USGS National Elevation Dataset (NED) [32].
- **Contiguous Areas < 1 sq. km**, which refers to fragmented land area polygons with an area of less than 1 square kilometer. These areas are too small to accommodate solar thermal power plants, which require relatively large land areas for the placement of collectors to reach a reasonable capacity. This assumption was also used by the NREL assessment of technical renewable potential [31].
- **Daily Direct Normal Insolation (DDNI) > 7.0 kWh/m^2/day**, which refers to areas with a daily direct normal insolation value of below 7.0 kWh/m^2/day. In California, all of the currently operating solar thermal power plants are sited in areas with DDNI greater than 7.0 kWh/m^2/day [24]. Deploying solar thermal power plants in areas with high DDNI give rise to improved energy production relative to power plant costs and therefore deployment in high DDNI areas are prioritized. These areas were determined by overlaying 10 km resolution direct normal insolation data from NREL [33] on the remaining land area and excluding the intersecting areas with a DDNI below 7.0 kWh/m^2/day.

A map of the lands excluded from solar thermal development in California described here is presented in Fig. 2:

2.1.2. Water-unconstrained installable solar thermal capacity potential calculation

We calculated the installable capacity for the remaining land areas. First, we calculated the annual energy obtained from a solar thermal power plant installed on each land area:

$$E_{gen,i} = DDNI_i \cdot \frac{365d}{1yr} \cdot A_{factor} \cdot \eta_{STE} \cdot A_i \tag{1}$$

where:

- $E_{gen,i}$ = The annual energy obtained from a solar thermal power plant deployed on land area i
- $DDNI_i$ = The Daily Direct Normal Insolation on land area i
- A_{factor} = The aperture-to-total land area ratio of a solar thermal power plant. This factor is defined as the fraction of the land area capable of collecting insolation. This accounts for land area use for collector spacing and other components of the power plant – e.g. steam turbine.
- η_{STE} = The solar-to-electrical efficiency of the power plant. This combines the collector efficiency along with the power block efficiency.
- A_i = The land area in square meters.

From the annual energy output, we derived the power capacity for each land area:

$$P_{cap,i} = \frac{E_{gen,i}/\Delta t}{CF} \tag{2}$$

where:

- $P_{cap,i}$ = The unconstrained installable solar thermal capacity on land area i
- $E_{\ gen,i}$ = The annual energy obtained from a solar thermal power plant deployed on land area i
- Δt = The period over which $E_{gen,I}$ is produced
- CF = The capacity factor of the power plant

The power capacities were then summed for land areas in each Hydrologic Region in California. This result sets the upper limit of installable solar thermal capacity for this study, representing the case where water constraints are not considered. We assumed the following values for the parameters of this calculation:

- A_{factor} = 0.2 and η_{STE} = 0.15 (15%)
  - o We extracted these values from information regarding the total land area, aperture area, design energy production, and total solar

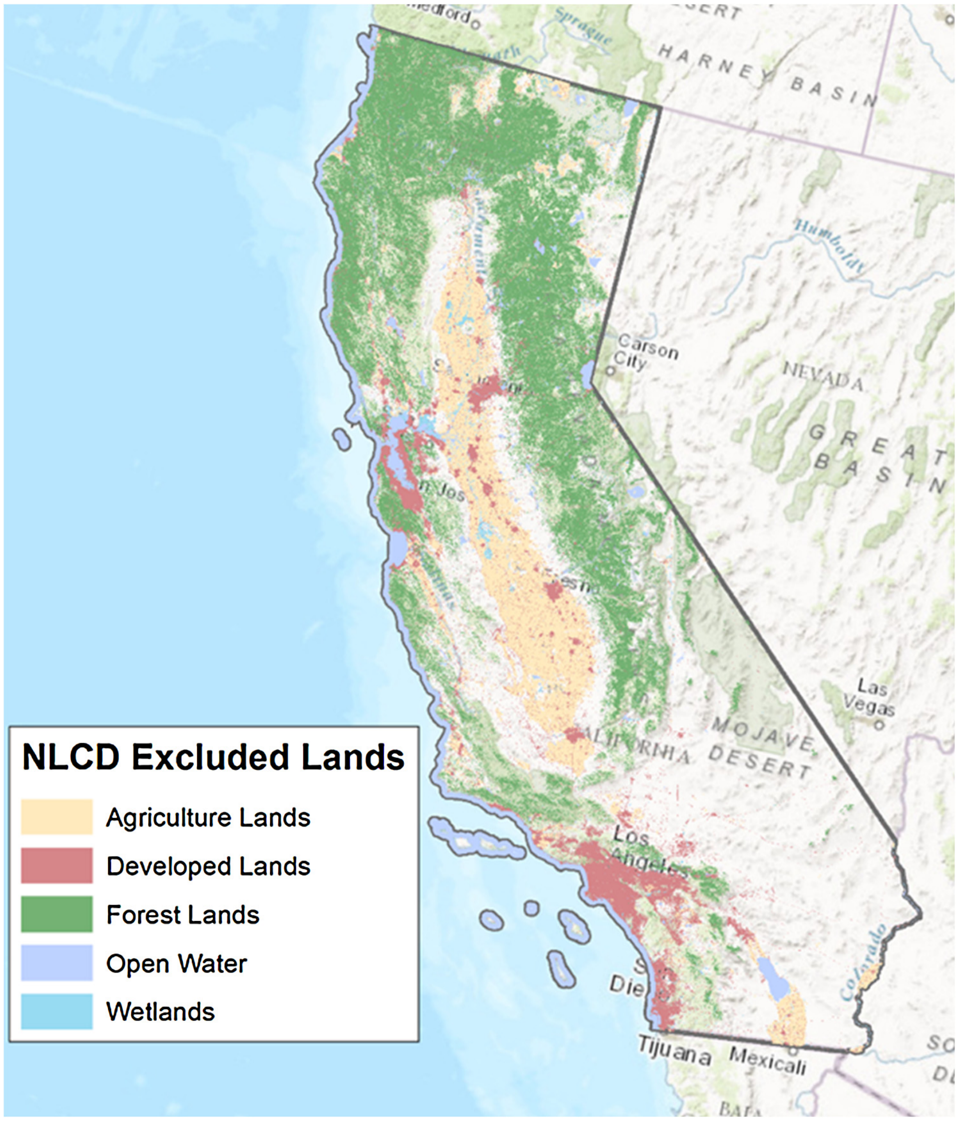

Fig. 2. Excluded land cover types from NLCD database.

energy collected for solar thermal power plants installed in California [24].

- *CF* = 0.28 (28%)
  - o We extracted this value from the capacity factors of solar thermal power plant production calculated in the HiGRID model, without storage [12].

2.1.3. Water-unconstrained installable geothermal capacity potential calculation

We established the water-unconstrained installable geothermal capacity potential from studies conducted by USGS [34,35]. Installable geothermal capacity can be split into two components: identified and unidentified hydrothermal resources. Identified hydrothermal resources refer to geothermal reservoirs which have been explored and determined to be suitable for geothermal power production. Unidentified hydrothermal resources refer to areas likely to be suitable for geothermal power production based on a number of geographic factors, but not yet explored.

To quantify identified hydrothermal resources, we used NREL's interface for displaying geothermal potential data [36] which displays data from a 2008 USGS assessment of geothermal capacity potential [34]. We grouped the resources by hydrologic region in California. We selected the datasets which displayed the capacity estimates corresponding with the mean of the range of estimates (mean probability) to be conservative in our analysis.

To quantify estimates for unidentified hydrothermal resources, we used a hydrologic regional-scale dataset generated with the geothermal favorability approach from the USGS resource assessment [34,35]. The USGS assessment estimated undiscovered geothermal resources for western states using a series of Geographic Information Systems (GIS) models to quantify the spatial correlation of geologic factors that facilitate the formation of geothermal systems. The approach uses the relationships between (1) characteristics of identified geothermal resources, (2) undiscovered constraints on the formation of geothermal systems, (3) spatial coverage of geothermal exploration to date, and (4) the effectiveness of the aforementioned exploration efforts [34,35]. The dataset was generated by analyzing each of California's hydrologic regions for undiscovered resources with a geospatial model for the favorability of occurrence for geothermal systems. Results from the regional scale modeling effort are reported by hydrologic region in Table 1.

To obtain the annual energy obtained for geothermal power plants, we assumed a capacity factor of 85%:

$$E_{gen,geo,i} = P_{cap,geo,i} \cdot CF \cdot \Delta t \tag{3}$$

Table 1
Total installable solar thermal and geothermal potential capacity by hydrologic region.

Hydrologic region	Water-unconstrained installable solar thermal capacity MW	Identified potential geothermal capacity MW	Unidentified potential geothermal capacity MW	Water-unconstrained installable geothermal capacity total MW
North Coast	0	1037.6	344	1381.6
San Francisco Bay	0	31.6	134	165.6
Central Coast	162.2	6.4	273	279.4
South Coast	339.9	17.8	110	127.8
Sacramento River	0	480.3	622	1102.3
San Joaquin	0	0	19	19
Tulare Lake	841.9	0	30	30
North Lahontan	682.7	173.1	253	426.1
South Lahontan	123995.5	499.6	504	1003.6
Colorado River	73626.4	3147.2	9051	12198.2
Sum	199648.6			16733.6

2.1.4. Solar thermal and geothermal resource summary

Table 1 presents the calculated potential for solar thermal and geothermal resources. The total geothermal capacity is the sum of the identified and unidentified geothermal capacity. A summary of the available geothermal sites and solar thermal lands is presented in Fig. 3. Fig. 3 is a result of the land exclusions conducted in Sections 2.1.1 and the geothermal analyses in Section 2.1.3.

2.2. Calculating net available water supply for each hydrologic region

For each hydrologic region, we performed a water balance to calculate net available water supply:

$$\frac{\partial S}{\partial t} = Q_{\text{in}} - Q_{\text{out}} \tag{4}$$

$$Q_{in} = P + F_{in} \tag{5}$$

$$Q_{out} = D + F_{out} + ET \tag{6}$$

where:

- $\frac{\partial S}{\partial t}$ = change in water storage in the region over time
- Q_{in} = water entering the region including precipitation (P) and streamflow
- Q_{out} = Outflows, evapotranspiration and consumption demand in the region
- P = precipitation over the given region
- F_{in} = Inflow into the region from other regions (includes natural and artificial flows)
- D = consumptive water demand in each region
- F_{out} = water outflows from the region (includes natural and artificial flows)
- ET = evapotranspiration

In each hydrologic region, we defined the Net Available Storage (NAS) as the amount of water available for supporting the water needs of solar thermal and geothermal resources.

$$NAS = mean(\Delta S | \Delta S(t) > 0) \tag{7}$$

where t is the time step (year) in the baseline and projection periods. We constrained NAS to positive values, as negative values would indicate unsustainable decreases in water storage over time.

The storage component used to calculate NAS is based on the water budget model described above. The storage includes both surface and subsurface water, but does not separate the two components. Additionally, the current analysis only considers freshwater resources (e.g. surface or groundwater) for use in supporting solar thermal and geothermal power plant cooling.

We represented the climate change-affected scenario by the years 2046–2055 and the historical baseline with the years 2001–2010. For the future scenario, we used precipitation data from Localized Constructed Analogs (LOCA) downscaled climate model simulations [37] and evapotranspiration data from LOCA downscaled simulations routed through the Variable Infiltration Capacity (VIC) hydrologic model [38]. VIC uses LOCA downscaled precipitation and temperature to estimate evapotranspiration, which introduces a level of uncertainty from the translation of meteorological to land surface conditions [39]. However, since each model possesses different spatial resolutions and considers different land surface processes, we used VIC derived evapotranspiration data to uniformly represent each climate model [39]. The model simulations are spatially resolved at 1/8th degree. We used CanESM2, CNRM-CM5, HadGEM2-ES, and MIROC5 climate models under the Representative Concentration Pathway 8.5 scenario. These four climate models were chosen by the California 4th Climate Assessment to represent the spectrum of climate change behaviors projected to occur in the state [39]. We averaged the meteorological data by hydrologic region and scaled by regional area size to obtain absolute water values for precipitation entering and evapotranspiration leaving each region. We obtained the historical baseline data from the California Water Plan Update 2013 volume 2 [37], which provided a breakdown of water entering and leaving each hydrologic region. See the SI for a summary and short description of the data for each hydrologic region.

For each climate model and hydrologic region, we perturbed the observed historical data of the parameters with the difference between the future and historical model simulations to obtain future precipitation and evapotranspiration data for the water balance:

$$\Delta P_{cc}(t) = P_{m,2046-2055}(t) - P_{m,2001-2010}(t) \tag{8}$$

$$\Delta ET_{cc}(t) = ET_{m,2046-2055}(t) - ET_{m,2001-2010}(t) \tag{9}$$

$$P_{cc}(t) = P_{a,2001-2010}(t) + \Delta P_{cc}(t) \tag{10}$$

$$ET_{cc}(t) = ET_{a,2001-2010}(t) + \Delta ET_{cc}(t) \tag{11}$$

where:

- $\Delta P_{cc}(t)$ = The difference in precipitation between the future periods and historical periods
- $P_{m,2046\text{-}2055}(t)$ = Modeled precipitation in 2046–2055 for each model
- $P_{m,2001\text{-}2010}(t)$ = Modeled precipitation in 2001–2010
- $P_{a,2001\text{-}2010}(t)$ = Actual data precipitation in 2001–2010
- $\Delta ET_{cc}(t)$ = The modeled difference in evapotranspiration between the future periods and historical periods
- $ET_{m,2046\text{-}2055}(t)$ = Modeled evapotranspiration in 2046–2055 for each model
- $ET_{m,2001\text{-}2010}(t)$ = Modeled evapotranspiration in 2001–2010
- $ET_{a,2001\text{-}2010}(t)$ = Actual data precipitation in 2001–2010
- $P_{cc}(t)$ = Projected precipitation in each hydrologic region used as

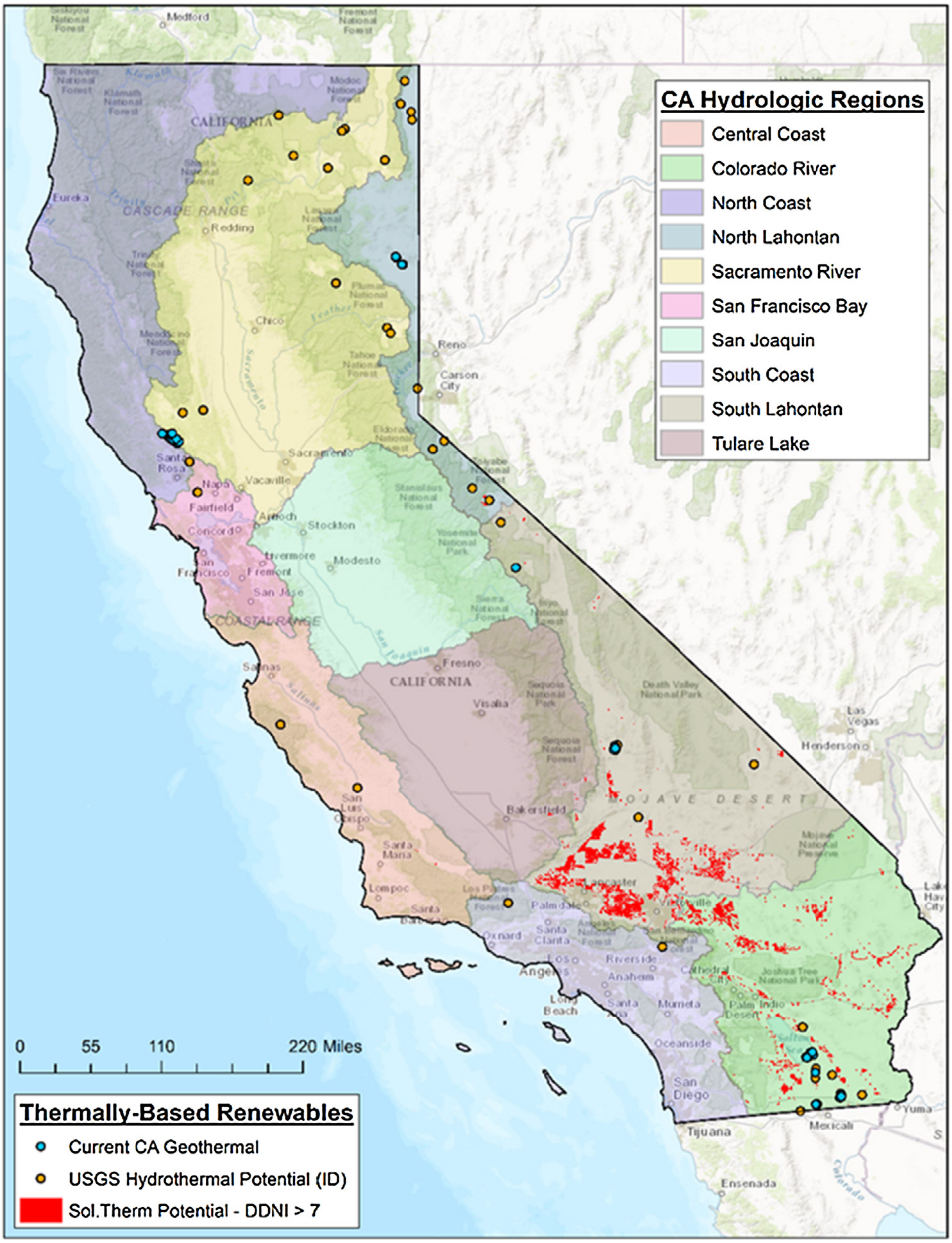

Fig. 3. Eligible solar thermal lands and identified geothermal sites in California.

input for the water balance model

- $ET_{cc}(t)$ = Projected evapotranspiration in each hydrologic region used as input for the water balance model

Depending on changes in population growth and density over the next few decades, urban and agricultural water demand will also influence the water balance. To determine water demand in each region, we used projected changes in urban and agricultural water demand from the 2013 California Water Plan Update [37] corresponding to the current trends scenario for population growth and population density. We utilized water demand projections that assume a continuation of the historical climate, since we account for the impacts of climate change explicitly and separately from water demand. The data used for changes in urban and agricultural water demand for each region are presented in the Supplementary Information. We considered two scenarios for regional water demand:

- **No Demand Change:** Regional water demand for non-energy sectors remain at present-day levels in each hydrologic region
- **With Demand Change:** Regional water demand for non-energy sectors change according to projected trends for population growth and population density from the 2013 California Water Plan Update.

2.3. Calculating the water-constrained installable solar thermal and geothermal capacity

Using the net available water supply for each hydrologic region under climate change, we calculated the water-constrained installable solar thermal and geothermal capacity. To accomplish this, we obtained observed NREL water consumption intensities of solar thermal and geothermal power plants equipped with different cooling systems [40]. For solar thermal resources, water consumption is represented by solar thermal trough systems, which have the most available data and represent an approximate average of different collector types. It is also important to note that while cooling is often the dominant use of water in power plants, the switch to dry cooling systems does not completely

Table 2
Water consumption factors for solar thermal and geothermal resources by cooling type.

Power plant type	Power plant technology	Cooling system	Water consumption range [m^3/MWh]	Median water consumption [m^3/MWh]
Solar thermal	Trough	Wet (Tower)	2.74–4.04	3.27
Solar thermal	Trough	Hybrid	0.39–1.30	1.28
Solar thermal	Trough	Dry	0.16–0.30	0.29
Geothermal	Dry steam	Wet (Tower)	6.80	6.80
Geothermal	Flash	Wet (Tower)	0.02–1.37	9.78
Geothermal	Flash	Dry	0.02	0.02
Geothermal	Binary	Wet (Tower)	6.43–15.0	13.6
Geothermal	Binary	Dry	1.02	1.02

eliminate water use. Water is also needed for working fluid make-up in the steam turbine power blocks, miscellaneous facilities for the workers, and cleaning of solar collectors when necessary. The values used in this study are presented in Table 2. Water-constrained capacity values were calculated for the minimum, maximum, and range of values.

Note that for some technology and cooling type combinations, reported variability is low or non-existent due to small sample sizes included in the NREL data.

The water-constrained annual energy obtained for each resource in each hydrologic region is calculated:

$$E_{gen,wc,i} = NAS_i \cdot \frac{1000AF}{1TAF} \cdot \frac{325851gal}{1AF} \cdot C_{factor}, \; (E_{gen,wc,i} > 0) \tag{12}$$

where:

- $E_{gen,wc,i}$ = The annual energy obtained from solar thermal or geothermal resources in hydrologic region i
- NAS_i = The calculated Net Available Storage in hydrologic region i
- C_{factor} = The water consumption factor corresponding to the power plant and cooling type combination being analyzed

The water constrained installable capacity for a given power plant type and cooling type combination is then calculated from the annual obtained energy using the approach outlined in Section 2.1.

Since NAS cannot be negative, regions with a negative water balance cannot support the additional water needs of future solar thermal and geothermal development and the corresponding installable capacity is set to zero. While it is possible for water to be imported from other regions to support a solar thermal and geothermal power plant, we did not consider this scenario as water transfer often leads to significant environmental impacts at the source and increased competition for water where the water is transferred to [41–43].

3. Results and discussion

3.1. Effects on solar thermal capacity deployment

The impact of water availability constraints on solar thermal resource deployment broken down into different cooling types (wet, hybrid, dry), and two regional water demand change scenarios relative to current-day water demands in Fig. 4. For each combination of cooling type and regional water demand scenario, the installable capacity is presented as a range (due to variability in the power plant water consumption data) and as a median value. For reference, a dashed line representing the potential installable solar thermal capacity without the constraints of water availability is included the figure. These values represent an average of the four climate models considered in this study.

Regardless of cooling type or water demand scenario, all future cases exhibit installable solar thermal capacity levels that are significantly lower than the unconstrained potential capacity. As expected, the wet cooling system cases are the most water intense and correspond with lower installable solar thermal capacities. Hybrid cooling systems allow relatively higher capacities and dry cooling systems allow the largest installable solar thermal capacities. However, even the combination with the highest installable solar thermal capacity only allows 105 GW of solar thermal capacity to be installed, which is only 52.6% of the unconstrained potential capacity. This occurs despite the very low total water use of the dry cooling systems and the reduction in water demand in other sectors projected by the demand change scenarios.

The limitation on installable solar thermal capacity constrained by water availability is primarily due to the location of where water resources are available relative to where solar thermal potential capacity is located. Recall from Sections 2.2 and 2.3 that the statewide results are composed from performing the water balance and resource potential assessment for each of the 10 hydrologic regions in California and combining the calculated potential from each region. The upcoming results present the details of water availability vs. water requirements to support solar thermal resources on a region-by-region basis to explain the behavior of the statewide results. After the land exclusions considered in this study, solar thermal potential is largely concentrated in the South Lahontan and Colorado River hydrologic regions. Changes in precipitation and demand that allow water to be available outside of these two regions do not significantly increase the solar thermal capacity that can be supported. This is reflected by Fig. 5, which shows the NAS requirements needed to support 100% of the unconstrained potential with wet, hybrid, and dry cooling systems compared against the historical NAS supply available in each hydrologic region. Note that while Fig. 4 displayed results for a range of water consumption values and water demand scenarios, Fig. 5 shows the regional breakdown but for the case using median water consumption values and no water demand change.

In Fig. 5, positive NAS values – indicating water availability – are present in most hydrologic regions. For the state of California, precipitation is projected to intensify in the northern regions of the state but decrease in the southern regions of the state such as the eastern desert areas. Total aggregated precipitation is expected to be similar to historical levels or greater based on the latest CMIP5 projections. Therefore, some regions project lower levels of available NAS in comparison to the water demand needed to fully support solar thermal deployment. In addition, San Joaquin River, Sacramento River, San Francisco Bay, and North Coast regions display high positive NAS values; however, these regions do not have eligible solar thermal capacity potential with the land exclusions considered in this analysis. Therefore, the available water resources in these regions do not contribute to supporting solar thermal capacity unless an arrangement of water transfers from other regions to solar thermal power plants is arranged, which was not considered in this study. The feasibility and desirability of such transfers from a resource sustainability standpoint depends on a case-by-case basis.

A second key observation is that the selection of the power plant cooling system only has a major effect when a positive NAS is present in the hydrologic regions where solar thermal resources are available. Utilizing a more water-efficient cooling system, such as hybrid or dry

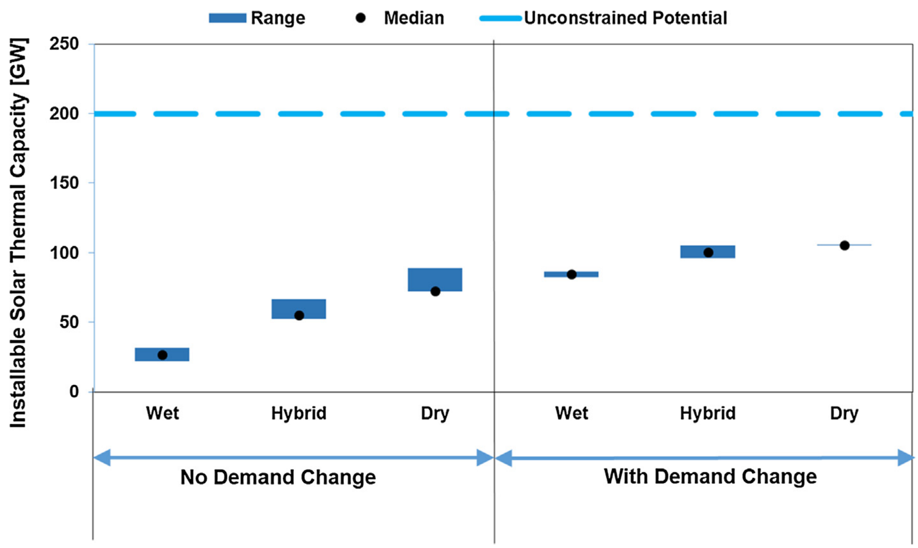

Fig. 4. Water constrained installable solar thermal capacity in California, unconstrained potential provided for comparison.

cooling, would allow the NAS present in a hydrologic region to support larger installable solar thermal capacities. However, if the NAS in a given region is zero, then solar thermal resources cannot be installed in that region regardless of cooling system type, since even with dry cooling, these facilities still require water.

Fig. 6 shows the projected changes in NAS supply with the NAS levels needed to support 100% of the unconstrained potential attached to each solar thermal cooling type. In the projections, water demand decreases in the Colorado River region due to increased urbanization and decreased agricultural land use by the year 2050. This allows more water to be available for use in supporting solar thermal power plant capacity, and allowing the full potential solar thermal capacity of the region to be installed. In contrast, the South Lahontan region shows a slight decrease in net available storage due to population change but still does not have enough resources to support the full potential solar thermal capacity of the region.

These results show that changes in water demand and efforts to reduce water usage in other sectors can increase the usability of thermal renewable resources.

Overall, for this case study and study area, the amount of installable

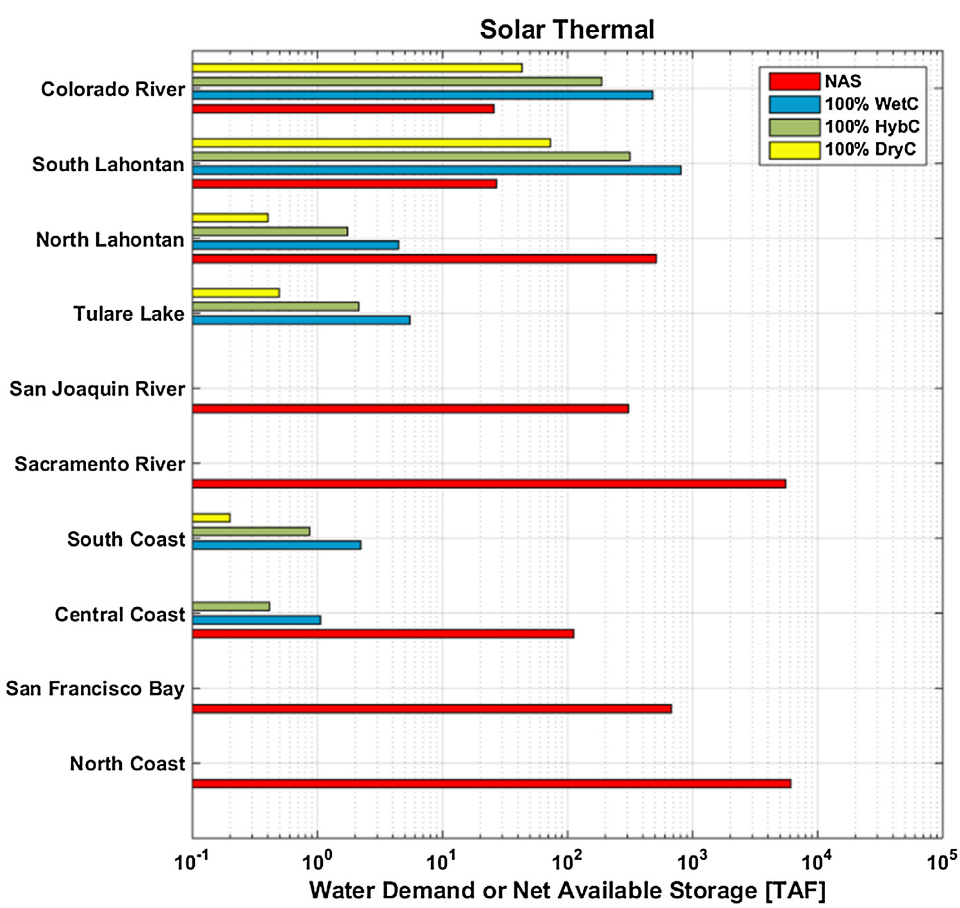

Fig. 5. Net available storage requirements for supporting solar thermal deployment in 2046–2055 – climate model average with no change in water demand from historical levels, compared with the calculated net available storage from the water balance. NAS = net available storage for a given region, 100% WetC = net available storage requirement to support 100% of installable solar thermal capacity with wet cooling, 100% HybC = net available storage requirement to support 100% of installable solar thermal capacity with hybrid cooling, 100% DryC = net available storage requirement to support 100% of installable solar thermal capacity with dry cooling.

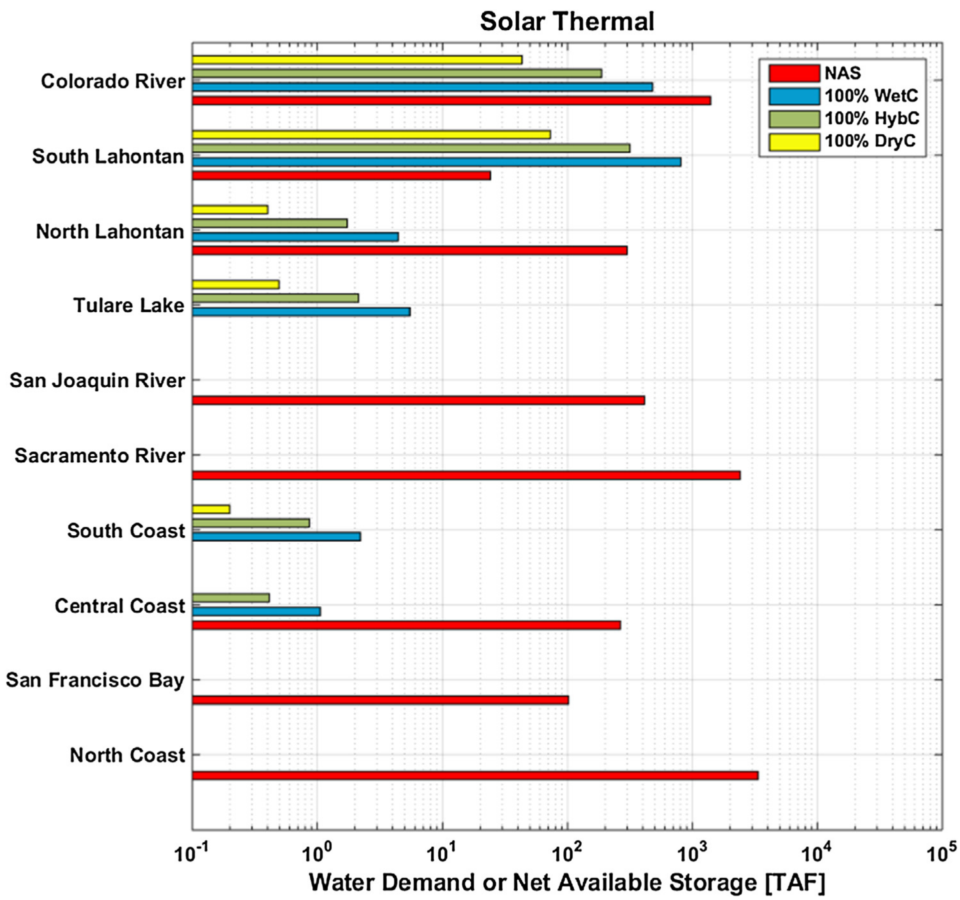

Fig. 6. Net available storage requirements for supporting solar thermal deployment in 2046–2055 – climate model average with projected future water demand levels, compared with the calculated net available storage from the water balance. NAS = actual net available storage for a given region, 100% WetC = net available storage requirement to support 100% of installable solar thermal capacity with wet cooling, 100% HybC = net available storage requirement to support 100% of installable solar thermal capacity with hybrid cooling, 100% DryC = net available storage requirement to support 100% of installable solar thermal capacity with dry cooling.

solar thermal capacity exhibited by the results is significant. Current E3 PATHWAYS projections for centralized solar capacity (PV or solar thermal) in long-term energy decarbonization plans are in the range of 94 GW for their Straight Line carbon reduction scenario by 2050. From Fig. 4, installing 94 GW of solar thermal capacity can only be achieved with regional water demand change or the use of dry cooling without water demand change. While this capacity can also be met by solar PV, understanding the resource limits on solar thermal capacity are important for planning and meeting long term decarbonization goals.

3.2. Effects on geothermal capacity deployment

The impact of water availability constraints on the potential for geothermal resource deployment is presented for different combinations of cooling type and geothermal technology with two regional water demand scenarios in Fig. 7. For each entry, the installable capacity is presented as a range (due to variability in the power plant water consumption data) and as a median value. For comparison, a dashed line representing the potential installable geothermal capacity without the constraints of water availability is overlaid on the figure. These values represent an average of the four climate models considered in this study.

Similar to the results for solar thermal capacity, all technology and cooling system types considering historical water demand levels show installable geothermal capacity levels lower than the unconstrained potential capacity of 16.7 GW. However, the installable geothermal capacity varies significantly between individual cases. Due to low water consumption, the dry cooling systems for flash and binary geothermal power plants allow high installable geothermal capacities of 8.67 and 7.71 GW, respectively. However, the wet cooling system for flash geothermal power plants has the potential to reach similar levels of installable geothermal capacity. Depending on the properties of nearby geothermal aquifers, geothermal fluid can be used in lieu of freshwater for cooling flash geothermal power plants; in these cases, freshwater inputs will only be needed for minor on-site water needs, such as facilities operation. As expected, the dry steam and binary wet cooling systems experience the greatest impact from water consumption. The reduction in installable geothermal capacity is due to limits on water availability in regions where geothermal potential is available. For example, the vast majority of geothermal potential is located in the Colorado River hydrologic region, where only a fraction of geothermal potential in the region can be supported without changes in regional water demand.

With regional demand change, all categories exhibit installable geothermal capacities very close to the unconstrained potential of 16.7 GW regardless of geothermal technology or cooling type. Projected decreases in agricultural land use in the Colorado River hydrologic region allow net available storage to fully support the geothermal capacity potential, and in all other regions of the state except Tulare Lake and South Lahontan. Fig. 8 highlights this with a regional breakdown of the net available storage compared to the water demand that must be satisfied to support the full potential of different combinations of geothermal technology and cooling system type.

Fig. 8 shows that the net available storage is sufficient to support 100% of the potential geothermal capacity in most hydrologic regions of the state with projected future water demand changes, with the net available storage being greater than the water requirements in all regions except Tulare Lake, South Coast, and South Lahontan.

Overall, these results indicate that water availability can constrain the ability to deploy geothermal power plant capacity to contribute towards decarbonization goals. In California, the current geothermal capacity is 2.72 GW [23] and the E3 PATHWAYS study plans for installed geothermal capacities in the range of 3.1 GW [1] by 2050. Therefore, even with water constraints, the installable geothermal

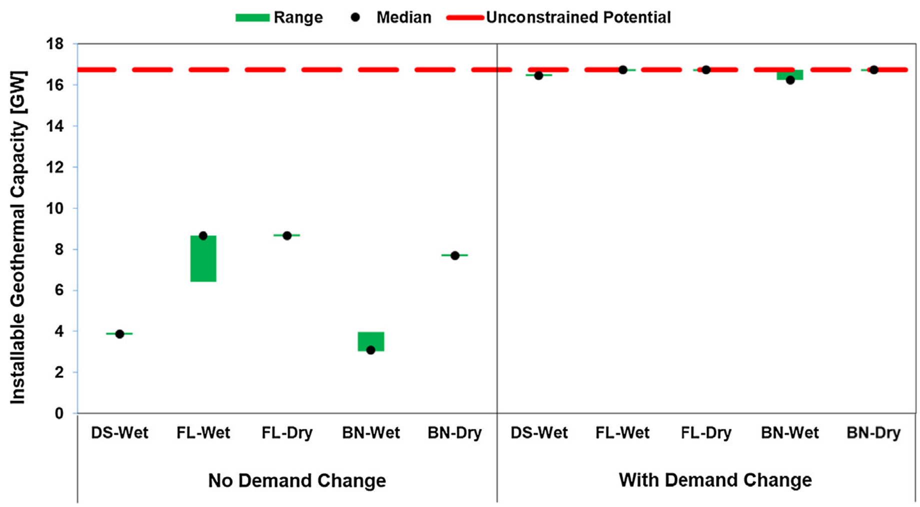

Fig. 7. Water constrained installable geothermal capacity in California, unconstrained potential provided for comparison. DS = dry steam geothermal, FL = flash geothermal, BN = binary geothermal.

capacity is still sufficient to comply with the future energy plan. In addition, due to projected changes in water demand in different regions across the state, these constraints can be largely lifted. This highlights the importance of changes in water use efficiency and land use spatially aligning with the distribution of geothermal resource potential.

4. Conclusions

In this study, we examined the effect of future water availability, influenced by climate change and regional water demand changes on solar thermal and geothermal resource utilization in California by the year 2050. We established the following conclusions:

Water availability can act as a limiting factor for the utilization of solar thermal and geothermal resources due to on-site water needs.

1. The spatial distribution of water availability drives the extent to which we can utilize solar thermal and geothermal resources. In order for solar thermal and geothermal resources to be utilized, water must be available in the hydrologic regions where significant solar thermal and geothermal resources are present. Resource

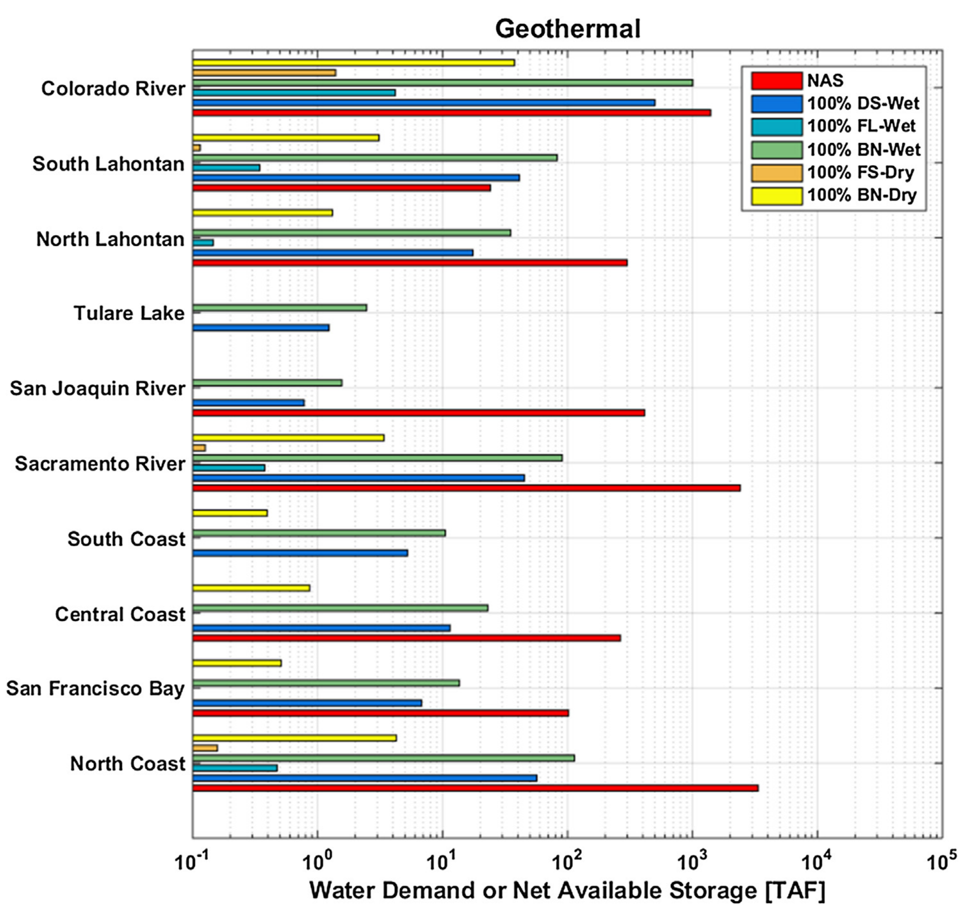

Fig. 8. Net available storage requirements for supporting geothermal deployment in 2046–2055 – climate model average with projected future water demand amounts compared with calculated supply. NAS = actual net available storage for a given region. Other bars refer to the water demand that must be available to allow 100% of geothermal potential in each region for specific combinations of geothermal technology and cooling system type.

potential is concentrated in the Colorado River and South Lahontan regions, and the water balance of these regions will be key drivers for utilization of these resources.
2. The type of cooling system only matters when the spatial distribution of water availability and resource potential aligns. If the water availability in a given region with solar thermal or geothermal potential is negative or zero, cooling system has no impact due to the restriction that dry cooling systems require on-site water for minor operations.
3. Reducing water demand in areas with high thermal renewable potential is key for maximizing utilization of these resources. When water demand change scenarios were implemented, all system types exhibited larger water constrained installable capacities. Reducing water demands in key regions, such as the Colorado River region, can free up water allocations for solar thermal and geothermal development, highlighting a potential synergy in the water-energy nexus.

5. Discussion

Overall, these insights have implications for determining the role of solar thermal and geothermal resources in renewable-based, low-carbon electricity portfolios for California. Our results have highlighted that solar thermal and geothermal resources must sustainably account for water resources and may not be viable resources in different regions of the state. Additionally, the deployment of solar thermal and geothermal suffers from potential resource risk: if large solar thermal and geothermal capacities are installed, some of these facilities may become inoperable if water shortage becomes a permanent reality. For solar thermal and geothermal resources to be deployed, operations must be streamlined to require as little water as possible and contingency plans must be established to ensure that power plants are not threatened by water shortage.

Solar thermal and geothermal resources may be competitors for available water resources. For California, however, only the Colorado River hydrologic region has both high solar thermal and high geothermal resource potential. Determining the optimal combination of solar thermal vs. geothermal deployment will depend on a number of practical factors such as costs and ease of operation. This is a topic for future work which can be useful for planning agencies and developers.

Accounting for the priority of other local water needs, the ability to access these water supplies, and limitations on remote solar thermal and geothermal energy transmission are also important topics for future consideration. Since most of the technical potential for solar thermal and geothermal energy is located in the southeastern desert regions of California, future power plants will need to be located in areas lacking nearby interconnection points to existing transmission infrastructure. Therefore, future studies must consider the costs of extending transmission infrastructure and creating interconnection points to allow the utilization of expanded solar thermal and geothermal resources.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2018.05.105.

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